NuMI Rookie Book

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1 Introduction

The NuMI Facility Project produces an intense beam of neutrinos to enable a new generation of experiments whose primary scientific goal is to definitively detect and study neutrino oscillations. The beam is of sufficient intensity and energy so that experiments capable of identifying muon neutrino (v_μ) to tau neutrino (v_τ) oscillations, as well as other possibilities, are feasible.

Interactions of the 120 GeV Main Injector proton beam in the NuMI target produce mesons, which are focused toward the beam axis by two magnetic horns. The mesons then decay into muons and neutrinos during their flight through a long decay tunnel. A hadron absorber downstream of the decay tunnel removes the remaining protons and mesons from the beam. The muons are absorbed by the subsequent earth shield, while the neutrinos continue through it to a near detector located in the MINOS Hall and beyond to the far detector in an underground laboratory in Soudan, Minnesota. The Fermilab and Soudan experimental halls house massive detectors specially designed to detect the small fraction of the NuMI beam neutrinos that interact in them. This experiment is called MINOS (Main Injector Neutrino Oscillation Search).

The NuMI Facility includes the underground enclosures as well as two service buildings located on the surface. The layout of the NuMI Facility underground enclosures is illustrated in Figure 1-1. An aerial photograph of the Fermilab site with the beamline superimposed is shown in Figure 1-2 and the trajectory of the neutrino beam between Fermilab and Soudan is shown in Figure 1-3. Because the neutrino beam must be aimed at the Soudan Underground Laboratory, the proton beam is directed downward at 58 mrad before it strikes the target.

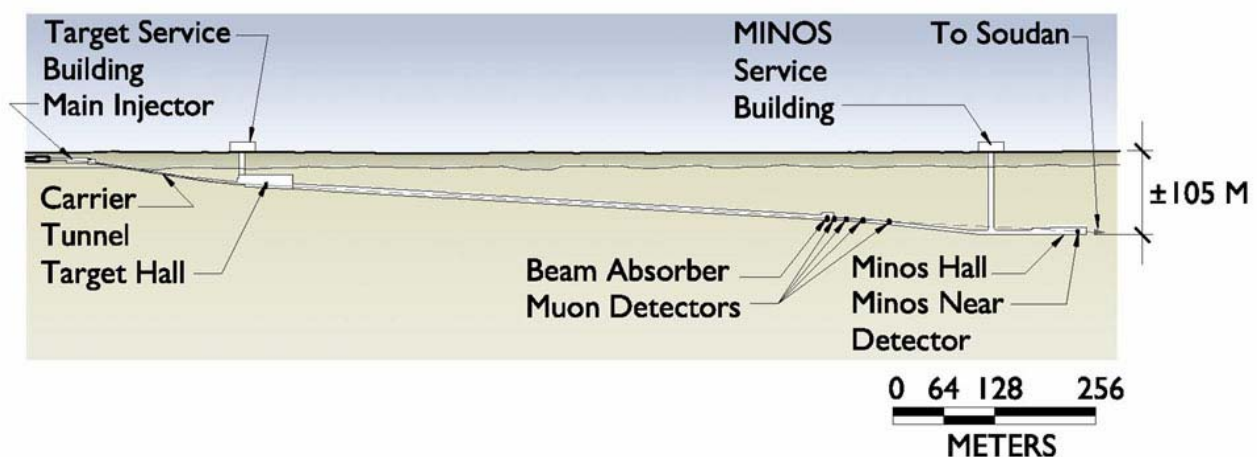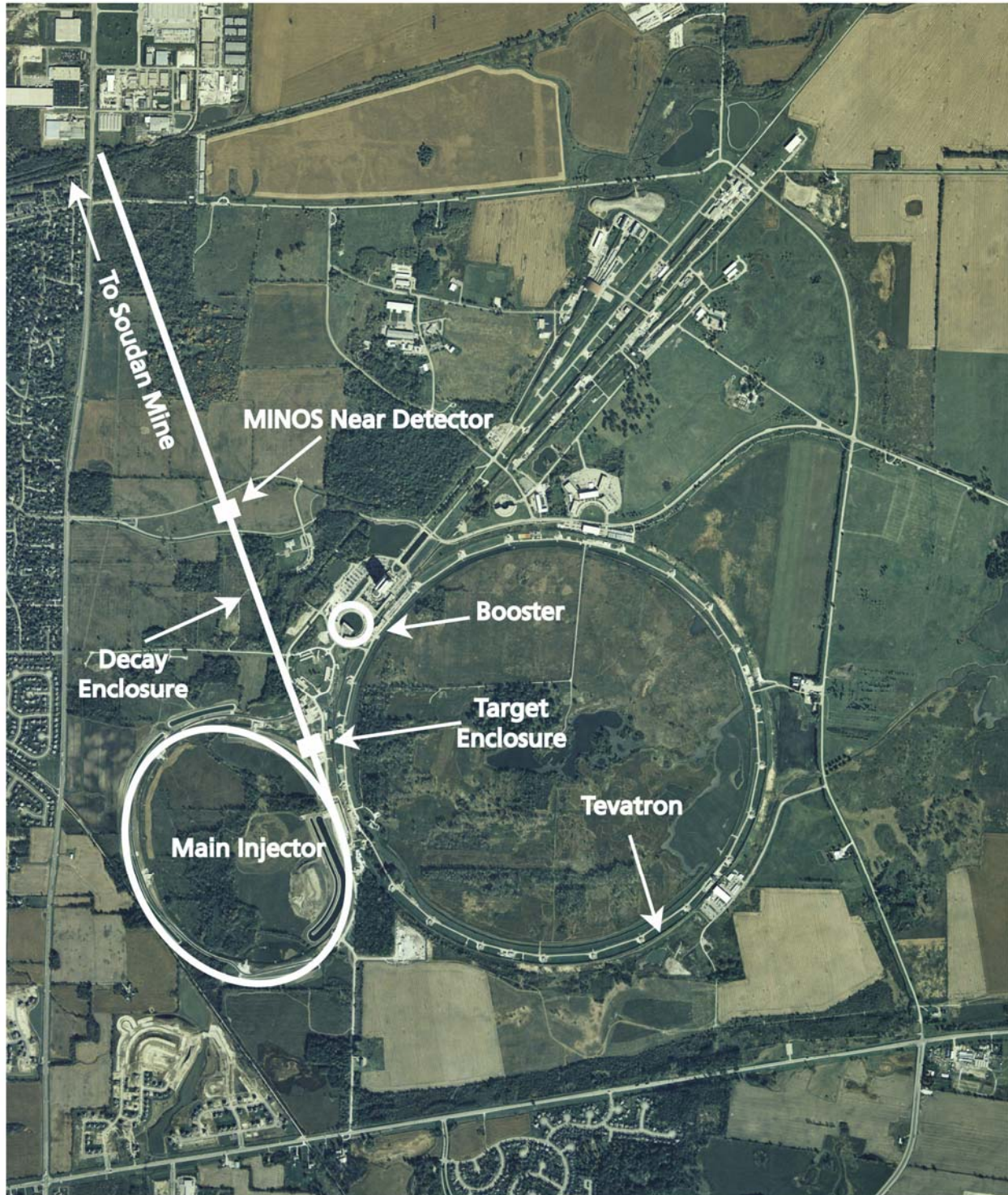**Figure 1-1** Layout of the NuMI Facility.

To Soudan Mine

MINOS Near Detector

Decay Enclosure

Booster

Target Enclosure

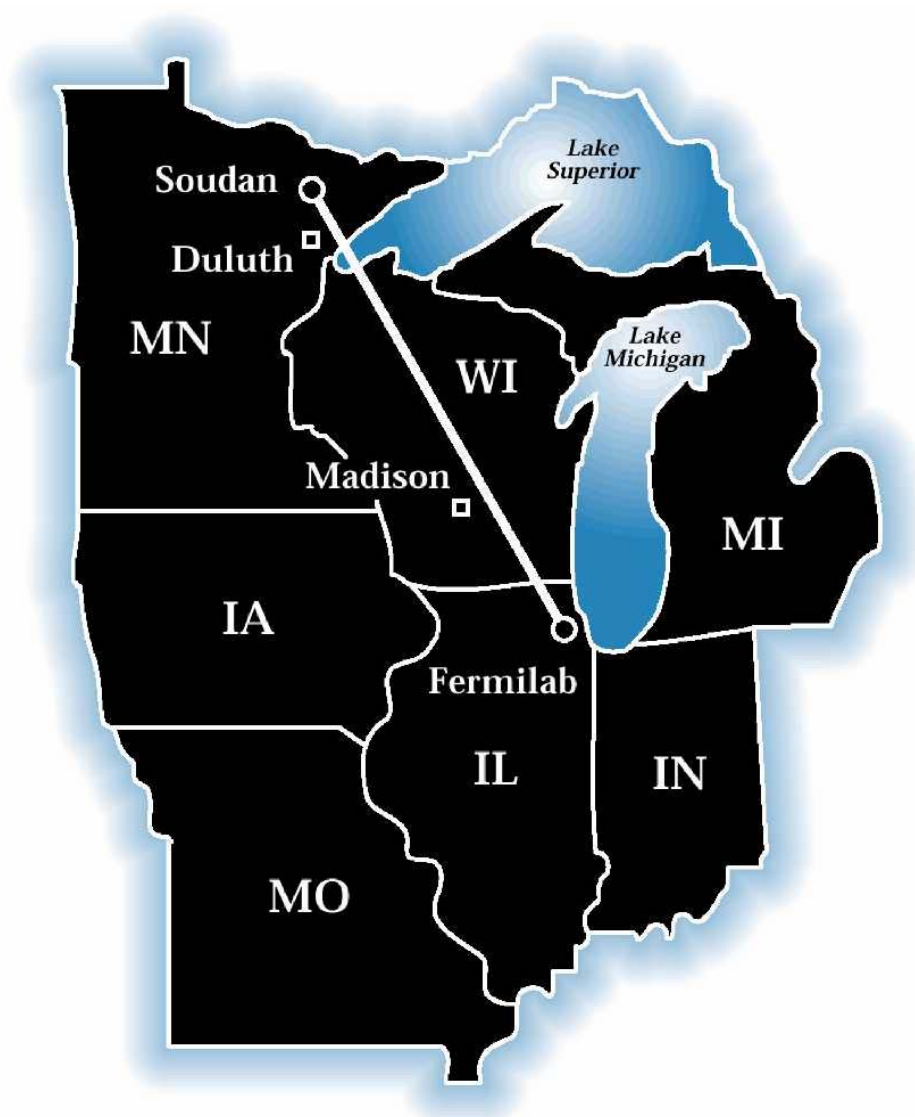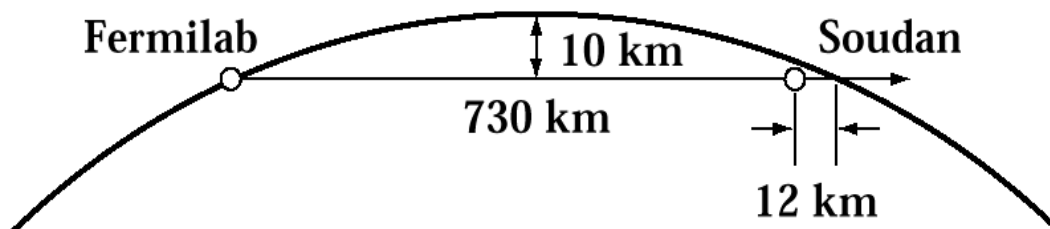Tevatron

Main Injector

FERMILAB #98-765D

Figure 1-3 Trajectory of the neutrino beam between Fermilab and Soudan, Minnesota.

Neutrino Production

The production target consists of 47 graphite segments. Each segment is 6.4 mm wide x 18 mm high x 20 mm long. The segments are soldered to water cooling lines. The target is surrounded by an aluminum jacket. A graphite baffle, located just upstream of the target protects the target cooling lines and the downstream horns. The baffle has an 11 mm circular hole for the beam and is air-cooled.

The target is followed by two focusing horns, which produce toroidal magnetic fields and act as lenses to focus the secondary particles along the proton direction. The neutrinos from the decays of the πs and Ks do not all follow the same path, but they are preferentially directed along the decay pipe axis. Thus the optimum design has all secondary particles directed toward the detector so that the resulting neutrino flux is maximized. However, in reality one can focus only some of the pions at all momenta or all of the pions at particular momenta, but not all pions at all momenta for all angles from the target.

NuMI has chosen horns with parabolic shaped inner conductors. These produce magnetic fields that act to first order as lenses, where the focal length is proportional to the pion momentum. Thus a selection of a particular target position causes a certain momentum to be focused by the first horn. Pions that were well focused by the first horn pass unaffected through a central aperture in the second horn. Pions that were somewhat over-focused or under-focused by the first horn move to larger radius and are focused by the second horn, extending the momentum bite of the system.

The pions actually pass through the current carrying inner wall of a horn to reach the focusing magnetic field. The design of a horn is a balance between trying to make the inner wall thin (to reduce absorption) and sturdy (since it is subjected to large pulses of electric current – 200 kA in the NuMI design). A water spray is used to keep the aluminum inner conductor below 100 C.

The particles selected by the focusing horns (mainly pions with a small component of kaons and un-interacting protons) are then allowed to propagate down an evacuated beam pipe (decay tunnel) 1 m in radius and 675 m long, placed in a tunnel, pointing downward towards Soudan. While traversing the decay pipe, a fraction of mesons decay, yielding forward-going neutrinos. By adjusting the energy of the parent meson beam, a neutrino beam in the desired energy range can be obtained.

All hadrons, including those primary protons that did not interact in the target, are stopped by a hadron absorber at the end of the decay pipe. Because the absorber is far downstream of the target, the natural divergence of the proton beam results in a larger spot size at the absorber, and the absorber does not have to handle nearly so high a deposition energy density as the target does. The absorber consists of a water cooled aluminum central core surrounded by steel.

The hadron absorber alone is too short to eliminate the muon component of the beam, which is produced from pion decays along with neutrinos. These muons must be absorbed before reaching the MINOS near detector. Muons can be eliminated by active shielding using large and expensive magnetic devices or by providing sufficient material to absorb their energy via multiple scattering. The NuMI beamline is located in dolomite, which is a dense rock. The 240 meters of dolomite between the end of the hadron absorber and the near detector is sufficient to stop all muons coming from the decay pipe.

The neutrino beam monitoring systems enable the beam users to measure the quality of the neutrino beam being delivered to the experiments. This is accomplished by measuring the flux and spatial distribution of hadrons directly upstream of the absorber and muons at several locations within the dolomite muon shield. Hardware problems with beamline and target components will be deduced from changes in these beams.

2 Design Parameters

This section summarizes the design parameters of the NuMI.

2.1 Proton Beam from Main Injector

Proton beam energy	120 GeV
Spill cycle time	1.87 sec
Bunch length	3-8 nsec
Batch length	84 bunches
Bunch spacing	18.8 nsec (53 MHz)
Emittance	40π mm-mr expected 500π mm-mr max
Momentum spread	2×10^{-4} $\delta p/p$ 2σ expected 23×10^{-3} $\delta p/p$ 2σ max
NuMI spill (Pbar operation)	5 batches x 84 + 4x3 = 432 bunches = 8.14 μsec
NuMI spill (no Pbar operation)	6 batches x 84 + 5x3 = 519 bunches = 9.78 μsec
Maximum intensity	4×10^{13} ppp (protons/spill)
Total beam power	404 kW at maximum intensity

2.2 Extracted Beam

Extraction method	Single turn – 3 kicker magnets
Position stability (transport)	$\pm$ 1 mm max
Beam size @ target	1 mm H x 1 mm V (σ)
Position stability @ target	$\pm$ 250 μ
Angular stability @ target	$\pm$ 60 μ-radian max
Max DC beam loss (MI region)	10^{-4} at maximum intensity
Max DC beam loss (Carrier pipe)	10^{-4} at maximum intensity
Max DC beam loss (Pre-target)	10^{-4} at maximum intensity

2.3 Instrumentation

Dynamic range	100 (= $4 \times 10^{13}/4 \times 10^{11}$ protons/spill)
Profile monitors	Multi-wire SEM

Number of wires/plane	48 of 0.003" gold plated tungsten wires
Transport region	3 H + 3 V 1 mm wire spacing, motor-driven
Pre-Target	2 H + 2 V 0.5 mm wire spacing ,motor-driven
Position reproducibility	< 50 μm
Intensity range	$2.5x10^{11}$ ppp to $4x10^{13}$ ppp
Channel signal/noise	100x over intensity range
Material in beam	$<10^{-5}$ loss
Beam position monitors	Cylindrical plate BPM
Transport region	6 H + 6 V
Position resolution	0.2 mm rms within $\pm$ 20 mm for $3x10^{10}$ to $9.5x10^{10}$ protons/bunch
Intensity resolution	$\pm$ 3%
Sampling	One sample per batch
Calibration	Electronics charge injection inter-spill
Pre-target	2 H + 2 V
Position resolution	0.05 mm rms within $\pm$ 6 mm for $3x10^{10}$ to $9.5x10^{10}$ protons/bunch
Intensity resolution	$\pm$ 3%
Sampling	One sample per batch
Calibration	Electronics charge injection inter-spill
Toroid intensity monitor	
Intensity resolution	3% absolute for > $1x10^{13}$ppp 30% for > $3x10^{11}$ppp
Stability	< 3% at > $1x10^{13}$ppp
Beam loss monitors	55 Sealed gas ionization chambers
Accuracy	$\pm$ 30% at $2x10^{8}$ppp
Dynamic range	$2x10^{8}$ to $4x10^{13}$ppp
Monitoring	High voltage status
Function	Sensitive to small localized losses
Total Loss Monitors	4 coax hose ionization, Ar-CO2 purged
Carrier pipe region	1 of 430' long, 2 of 215' long
Pre-target region	1 spanning the entire region
Accuracy	$\pm$ 30% at $2x10^{8}$ppp
Dynamic range	$2x10^{8}$ to $4x10^{13}$ppp
Function	Sensitive to large losses

2.4 Neutrino Beam Devices

Baffle/Target Module

Module motion control	
Baffle	
composition	Graphite

aperture	5.4 mm H x 12 mm V
length	2 m
motion control	~10 cm H (manual drive)
cooling	Air or RAW under consideration
Target	
composition	Graphite segments (Poco ZXF-5Q)
length	47 of 20 mm long segments, 0.3mm spacing
density	1.686 ± 0.025 gm/cm^3
width	6.4 mm
height	18 mm
cooling	RAW cooling tubes top/bottom of fin
distance from horn 1	35 cm to Monte Carlo upstream end
motion control	~1 m Z insertion into Horn 1

Neutrino Horn 1 Module

Horn shape	Double Parabolic
Construction	Nickel plated aluminum inner conductor Anodized aluminum outer conductor
Minimum aperture field-free neck	9 mm radius
Inner conductor thickness	2 mm (min) – 4.5 mm (max at neck)
Outer conductor	11.75 inch I.D. 13.75 inch O.D.
Horn Length	300 cm focus region, 132 inches overall
Current	200 kA
Motion control	± 1 cm H x ± 1 cm V each end (motor drive)
Horn cooling	RAW spray, 30 gal/min

Neutrino Horn 2 Module

Horn shape	Double Parabolic
Construction	Nickel plated aluminum inner conductor Anodized aluminum outer conductor
Minimum aperture field-free neck	3.9 cm radius
Inner conductor thickness	3 mm (min) - 5 mm (max)
Outer conductor	29.134 inch I.D. 31.134 inch O.D.
Horn Length	300 cm focus region, 143 inches overall
Current	200 kA
Motion control	None
Distance from Horn 1	10 m (upstream end H1 to upstream end H2)
Horn cooling	RAW spray, 30 gal/min

2.5 Power Supply Systems

Kicker Power Supply :   Single pulse forming network, drives 2 magnets in parallel

Conventional Power Supplies Regulation requirements

Lam60	200 ppm
V100	400 ppm
HV101	65 ppm
V104	200 ppm
V105	60 ppm
V109	200 ppm
V110	55 ppm
Trims	0.1%
Quadrupoles	400 ppm

Horn Power Supply : Series connection to Horn 1 and Horn 2

Peak current	240k A
Operating current	200k A average $\pm$ 2.5%
Current monitoring	0.4%
Operating voltage	800 V
Repeatability	$\pm$ 1% pulse to pulse
Pulse width	~half-sine 1.7 ms @ base
Pulse period	1.9 sec

Horn Stripline

Construction	30 cm x 10 cm Aluminum strips, 1 cm spacing
Resistance	10 $\mu\Omega$/m
Inductance	16 nH/m

2.6 Decay Pipe

Size	1.98 m inner dia x 677.1 m long
Vacuum	<1 Torr
Upstream vacuum window	1.57 mm aluminum
Downstream vacuum window	6.35 mm steel

2.7 Hadron Absorber

Primary beam size at Absorber (target out)	5.4 cm H x 7.9 cm V (1 σ)
Primary beam size at Absorber (target in)	29 cm (rms)
Beam power - normal	64 kW (82% primary protons, 18% secondaries)
Beam power - accident	404 kW
Accident condition	1 hour (1900 pulses) mis-targeted primary proton
Absorber core	8 aluminum modules + 10 steel CCSS layers
Aluminum modules	1.29 m H x 1.29 m V x 30 cm Z RAW cooled
Steel CCSS layers	1.29 m H x 1.29 m V x 23 cm Z
Max temperature - normal	60 ^{o}C in aluminum modules 3 and 4 270 ^{o}C in steel module 1
Max temperature - accident	160 ^{o}C in aluminum modules 3 and 4 800 ^{o}C in steel module 1

2.8 Secondary Beam Monitoring

Station	Maximum Flux/spill
Hadron Monitor	2.5×10^{9}/cm^2
Alcove 0 Muon Monitor	3.2×10^{7}/cm^2
Alcove 1 Muon Monitor	1.7×10^{7}/cm^2
Alcove 2 Muon Monitor	0.22×10^{7}/cm^2

2.9 Water, Vacuum & Gas Systems

CUB = Central Utility Building	CW = Chilled Water
LCW = Low Conductivity Water	PW = Pond Water
RAW = Radioactive Water	SB = Service Building

Power dissipation

Beam transport magnets	628 kW
MI-62 LCW system	700/1200 (kW nominal/max) to MI Pond G
MINOS LCW system	108/200 (kW nominal/max) to MINOS SB CW
Absorber RAW	60/200 (kW nominal/max) to MINOS SB PW
Decay pipe RAW	150/200 (kW nominal/max) to CUB CW (1/2) and MINOS SB CW (1/2)
Target RAW	10/25 (kW nominal/max) to MI62 LCW
Horn 1 RAW	40/200 (kW nominal/max) to CUB CW
Horn 2 RAW	10/50 (kW nominal/max) to CUB CW

Vacuum

Main Injector extraction region	10^{-8} Torr
Primary beam transport vacuum	$<10^{-6}$ Torr
12" Carrier pipe	10^{-5} Torr
Hadron Decay Pipe vacuum	0.1 to 1 Torr

3 NuMI Areas

The NuMI beam is extracted from the Main Injector in the 600 region. Planning for NuMI was underway during the Main Injector construction, and an extension called the "NuMI stub" was built. A lower elevation extension to the NuMI stub called "Peter's Porch" was added during NuMI construction. From Peter's Porch, the beam enters the Carrier Tunnel, spanning the geologic regions of glacial till to the hard rock dolomite. There are two separate regions to the Carrier Tunnel, called "Upper Hobbit" and 'Lower Hobbit". Upper Hobbit is constructed of 6' diameter concrete sewer pipe and is rarely accessed. The only components in Upper Hobbit are a 12" diameter beam pipe and an ion pump. In general, areas upstream of Upper Hobbit are accessed from the Main Injector, and areas downstream of Upper Hobbit are accessed from MI-65.

Lower Hobbit was constructed and finished like most NuMI underground areas. The areas were excavated using drill and blast methods. The walls and roof were strengthened by epoxy coated rock bolts. A porous mesh was attached to the interior surfaces of the rock, and drainage tile was laid on the floor. Shotcrete was then sprayed onto the mesh. The porous mesh serves to divert the majority of the in-flowing water to the drainage tile. A finish concrete floor was then poured with additional drain channels.

3.1 MI-65

The MI-65 Service Building (Fig 3.1-1) is the underground access point for Lower Hobbit, Pre-Target and Target Hall and contains power supplies and controls for these areas. The mezzanine houses HVAC equipment, including a large desiccant unit to supply dry air underground.

Below-ground access is possible after underground access training is completed. When the Target Hall and Pre-Target areas are secured, the underground occupancy limit is 8 persons. During controlled and supervised access there is no occupancy limit. These occupancy limits are driven by several considerations; below-ground space, ventilation and emergency egress routes and methods. The occupancy limits are administered by providing an elevator access key and badge for each entrant. Detailed access procedures are described in the underground access training.

The decay pipe passageway is accessible from the downstream end of the Target Hall and also from the Absorber Hall. The decay pipe passageway is used solely as an emergency egress and is secured separately.
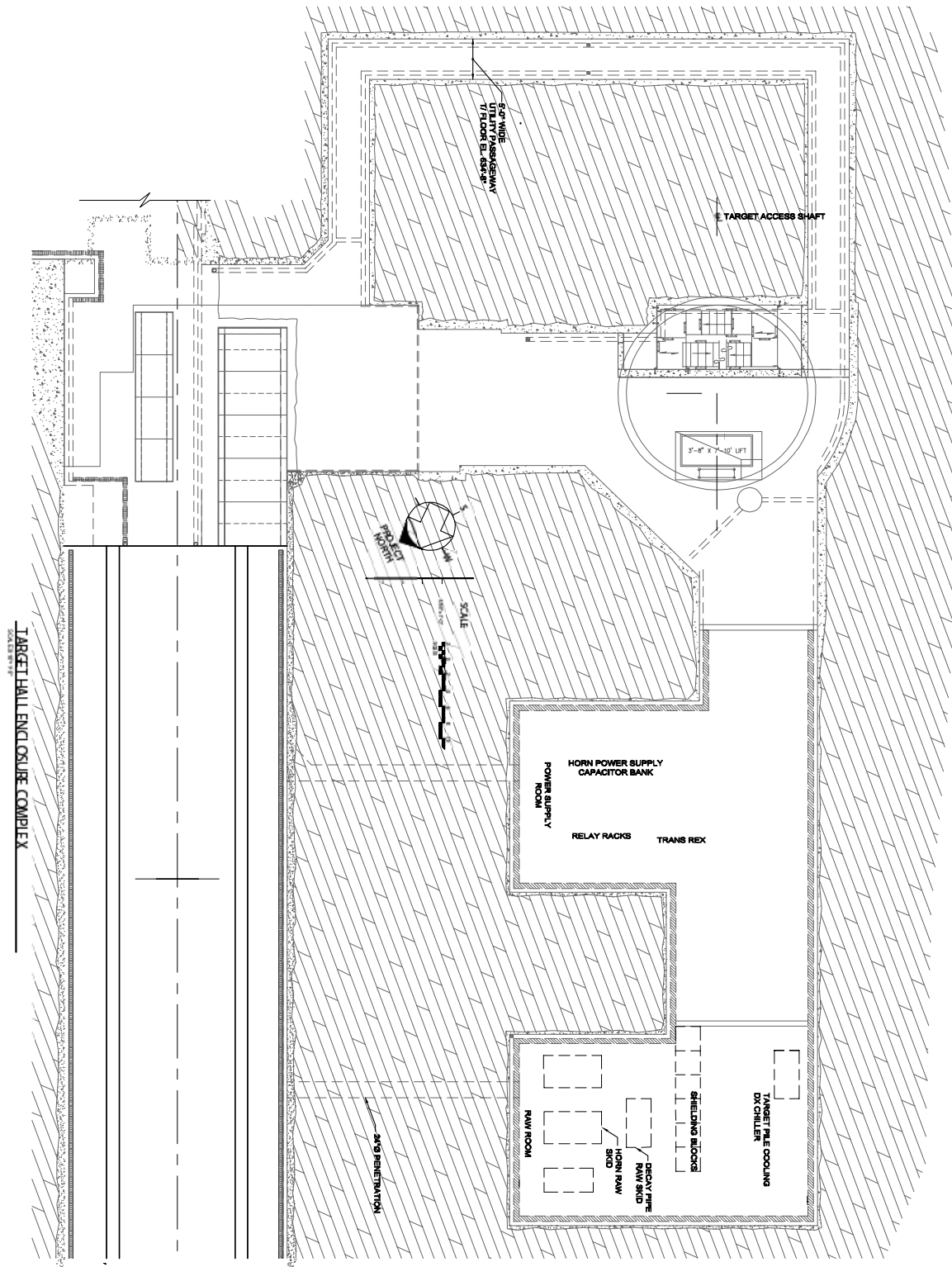
Figure 3.1-1 MI-65 Service Building
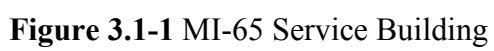
Figure 3.1-2 MI-65 Below Ground

3.2 MINOS

The MINOS service building is the underground access point for access to the MINOS detector hall, the Absorber Cavern, Absorber Access Tunnel and the muon alcoves. The Particle Physics Division is the landlord for the MINOS service building and all underground areas downstream of the fire door at the base of the shaft.

Underground access requirements are somewhat different than MI-65 due to the increased depth of the underground area. There is no stairway egress to the surface. Emergency egress is via the shaft elevator or the decay pipe passageway to the Target Hall. An emergency generator provides power for the elevators in the event of a power outage. There are two elevators in the MINOS shaft. The smaller elevator is reserved for use by the Fire Department. During supervised or controlled access, the below ground occupancy limit is 26 people; the maximum that can be transported to the surface in two elevator trips. A maximum of 10 people may be underground when the Absorber Hall is secured. There is no LOTO requirement for access to the Absorber Hall or muon alcoves.

Underground access keys are held in the Main Control Room and the MINOS control room on the 12th floor of Wilson Hall. A small number of keys are also held by the Fire Department and FESS Operations.
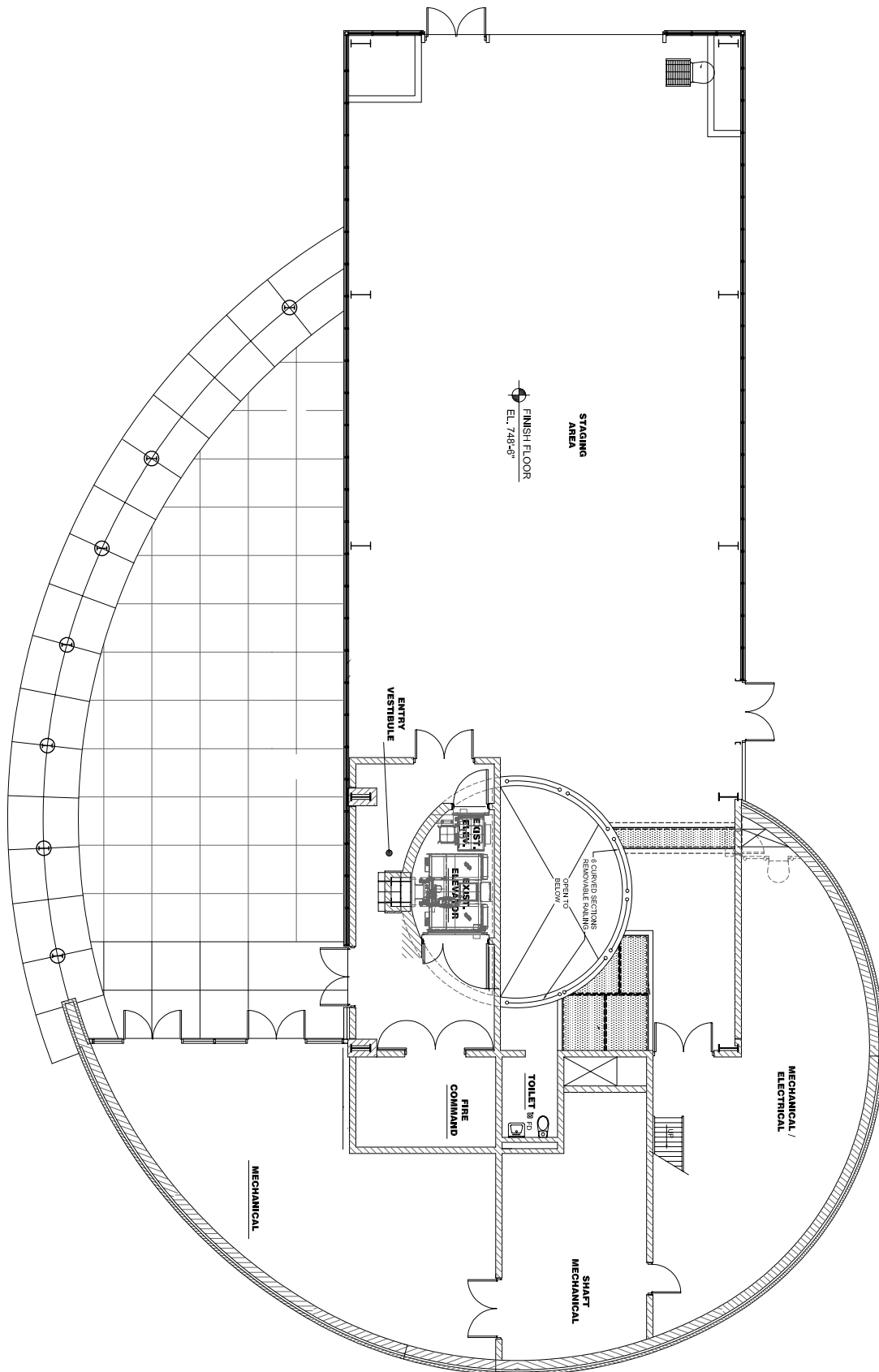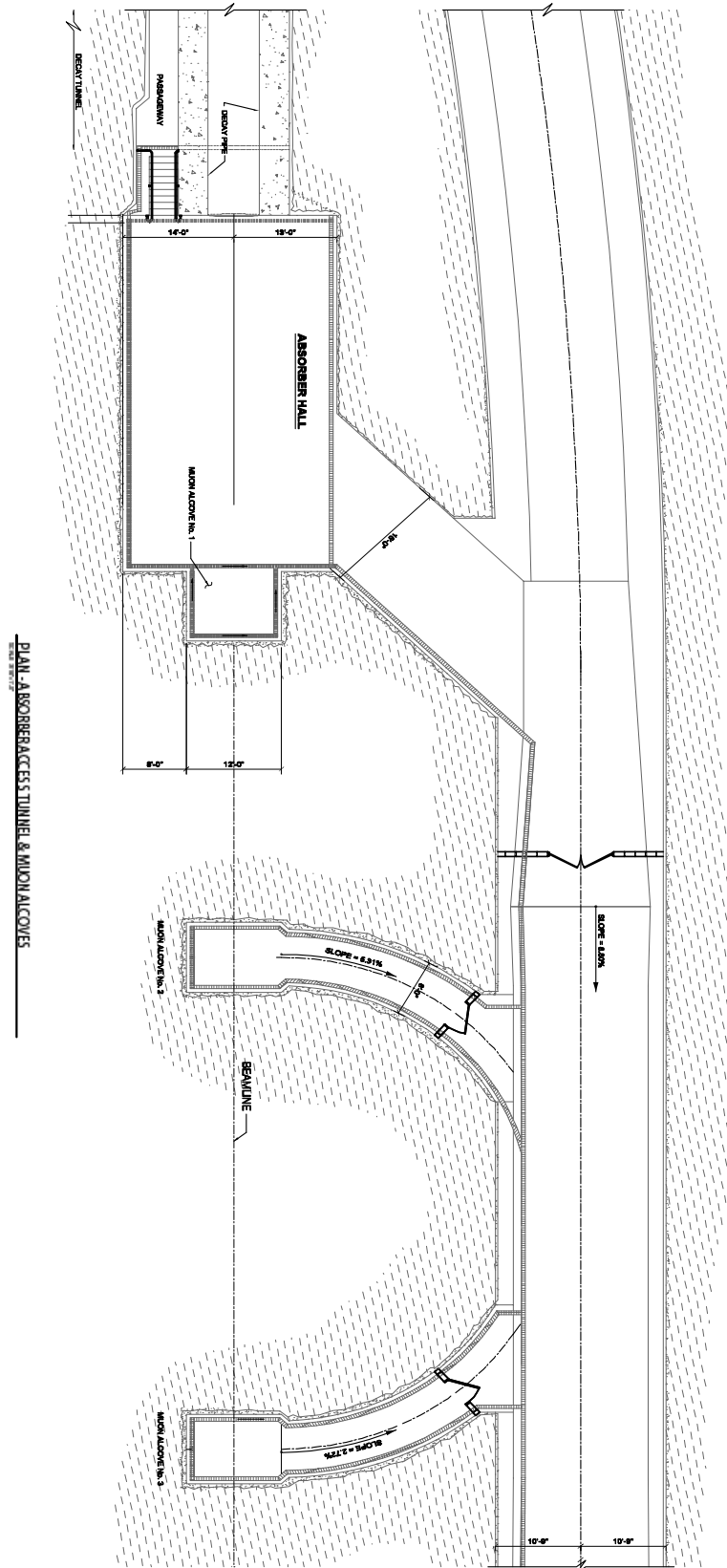
Figure 3.2-1 MINOS Service Building

Figure 3.2-2 Absorber cavern, muon alcoves and access tunnel

4 Beam Components

4.1 Extraction & Transport

The requirements on the extraction kicker were originally thought to be similar to those of the long-batch kicker which used to be operational at MI52. However the MI52 extraction region was found to be quite activated. Simulations show that the two kicker configuration which precedes it does not provide enough kick to clear the Lambertson magnet septum cleanly. Since the NuMI extraction region must transmit roughly five times as much beam as MI52 does with a larger transverse emittance, it was decided to construct three rather than two kicker magnet modules. The three magnets together supply 3.8 kG-m of integrated field, and achieve adequate separation at the Lambertson.

The normal mixed-mode operation is one Main Injector batch extracted to Pbar and five Main Injector batches extracted to NuMI; on the same acceleration cycle. Each batch consists of 84 18.9 nsec bunches. However for periods when Pbar is not in a stacking mode it will be desired to extract six Booster batches to NuMI. This latter mode has essentially the same requirements as did six-batch extraction to the Tevatron, which was effected by the MI52 long batch device. The magnets are located in the region downstream of quadrupole Q602.

A complication is that the strongly focusing MI lattice requires that quadrupole Q608 is located between the Lambertsons. One effect is that the extracted beam passes through this magnet off-center and suffers considerable quadrupole steering. This steering must be counteracted by a horizontal kick from the Lambertsons and thus the first two are rolled to provide an outward deflection in what is primarily a vertical bend. A second problem is that the restriction created by the vertical kick by Lambertson 1 and the aperture of the quadrupole. Due to this effect the first Lambertson is run at a reduced current. To effect extraction Lambertsons 2 and 3 must be run somewhat above their nominal value, though still within their specified current limit.

The final extraction element is a standard MI C-magnet, installed as a pure vertical bend and positioned as far upstream as possible given physical constraints.

The beam transport consists of three bend regions with quadrupole focusing in the straight sections connecting them. The quadrupole layout and design principles are discussed in detail in TM-2174 (May 28, 2002; John Johnstone, author).

There are 21 quadrupoles in total. The first 15 provide a match with the MI optics, a suitably focused transfer through the MI tunnel and a well-behaved passage through the carrier region where no components are installed. The last 6 form the final focus optics to obtain the desired beam size and minimum dispersion at the target. The final focus section is optically flexible and can comfortably accommodate tuning to different beam sizes and shapes.

4.2 Power Supplies

Table 4.2-1 summarizes the number and types of power supplies needed for the NuMI beamline. For beam tuning and focusing, each trim and quadrupole magnet has its own power supply. On the other hand the bend circuits use several 500 kW supplies in series (or for the V108 circuit a Main Ring Power Supply) in order to obtain the desired voltage levels. All power supplies are standard refurbished FNAL power supplies, with the exception of the kicker power supply and horn power supply. The kicker and horn power supplies are designed and built specifically for the NuMI application. The horn power supply uses a transmission line to supply current to the two horns. The kicker power supply uses standard RG220 cable. The following sections describe the power supply system, starting with the conventional, mostly refurbished power supplies, then the kicker power supply and finally the horn power supply and its transmission line.

Type	Number
Kicker Power Supply (requires a 60 kV charging power supply)	1
Horn Power Supply (requires 2 charging power supplies and a transmission line)	1
PEI 240 kW (horn power supply charging power supplies)	2
Main Ring Style	1
PEI 500 kW	10
PEI 20 kW	23
MI Correction element power supplies	19

Table 4.2-1 Summary of Power Supplies and Types

All magnet supplies are ramped. There are seven high-current bend circuits: the kicker magnet (I:KPS6N), the first Lambertson magnet (I:LAM60), the second and third Lambertson magnets (I:LAM61), the C-magnet (E:V100) and three bend circuits (E:HV101, E:V108, E:V118). The power supplies are located in three areas, MI-60, MI-62 and MI-65. The extraction system power supplies (I:KPS6N, I:LAM60, I:LAM601, E:V100, E:HV101), the first 12 corrector element power supplies, and the first 6 quad power supplies are located in MI60. The second bend power supplies (E:V108), one 20 kW power supply (E:H104), and 6 quad power supplies are located in MI62. The final bend power supply (E:V118), one 20 kW power supply (E:H117), 9 quad power supplies and 9 corrector power supplies are located in MI-65.

The first Lambertson magnet, due to aperture restrictions in quad Q608 downstream of it, is run at a lower current than the last two Lambertson magnets. Thus there are two separate 500 KW power supplies for the three Lambertson magnets (I:LAM60, I:LAM61). The C-magnet is powered by a 500 kW supply (E:V100). The first bend string (E:HV101) consists of six EPB magnets powered by three 500 kW supplies in series. The second bend (E:V108) consists of six B2 magnets powered by a Main Ring type power supply. The circuit E:V118, the four B2 magnets, is powered by a four 500 kW supplies, run as 2 sets of 2 500kW supplies in series. There are also 21 quadrupole

circuits, each with a 20kW power supply and two dipole circuits, each with a 20kW power supply. There are nineteen low-current circuits for Main Injector corrector magnets. The critical devices are the E:HV101 and I:LAM61 circuits. Standard FNAL hardware is used for the critical device circuits.

4.3 Instrumentation

The instrumentation of this beamline is designed to serve two purposes. The first is to assure that the beam is accurately on target and is directed accurately toward the far detector. The pointing requirement on the primary beam, 60 μrad, is about as stringent as those requirements of other fixed target experiments. The second purpose of the instrumentation is to aid in the effort to keep any losses at an minimum level. It will do this by providing: position information to assure that the beam is in the center of its vacuum chamber, profiles to allow unexpected beam tails and halo to be observed, sensitive loss measurements to allow beam problems to be immediately addressed and intensity measurements in the ring and in the line to serve redundantly with the loss monitors in the case of large losses.

All of the instrumentation is the same as that in the accelerator complex, except for the profile monitors. The difference is that NuMI transports unprecedented beam intensities at this energy with the concomitant requirement for rigorous control of beam loss. This places a stringent requirement on beam instrumentation precision, calibration and robustness.
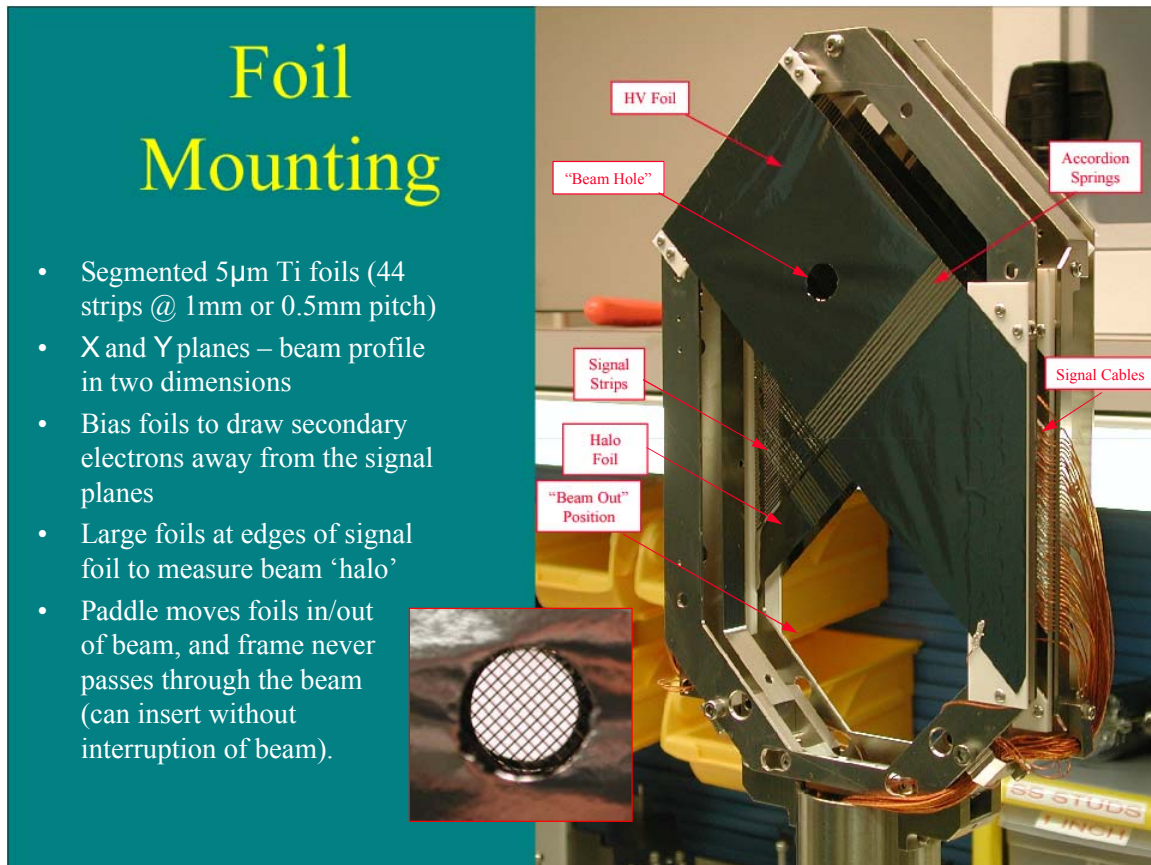
Profile Monitors

Transfer lines typically use a standard Fermilab multi-wire; an array of wires rotated into the beam to measure the transverse beam size. It is desirable to measure the transverse beam profile at the highest intensity possible since transverse emittance increases with intensity. Beam loss from the standard multi-wire 75 μm tungsten wires is unacceptable for NuMI. The standard multi-wire design also requires that the frame supporting the wires passes through the beam necessitating beam interruption during insertion.

MINOS collaborators from the University of Texas at Austin have developed profile monitor based on a design used at CERN where the wires are replaced by thin (5 μm) titanium foil strips. Foil insertion is accomplished by a bayonet design which allows insertion during beam operation. The foil strips are mounted at a 45° angle relative to the device and the device is mounted on a 45° stand to measure the usual horizontal and vertical profiles.

The two planes of foil strips are separated by high voltage foils which collect the secondary electrons created by the beam. The HV foils have a 10 mm diameter hole through which the beam passes when it is on-axis. If the beam is steered off-axis by more than 5 mm, beam losses will increase 10x compared to the on-axis condition. If the beam out of the Main Injector is badly off the normal trajectory and all profile monitors are IN, the beam permit may trip due to high beam loss.

Care should likewise be taken while inserting profile monitors at high intensity since the beam will hit the HV foils during insertion. Beamline operators have the option of disabling the NuMI beam switch or ensuring that only one profile monitor is inserted or retracted at a time.

Foil Mounting

- Segmented 5μm Ti foils (44 strips @ 1mm or 0.5mm pitch)
- X and Y planes – beam profile in two dimensions
- Bias foils to draw secondary electrons away from the signal planes
- Large foils at edges of signal foil to measure beam 'halo'
- Paddle moves foils in/out of beam, and frame never passes through the beam (can insert without interruption of beam).

BPM's

There are specified 24 position/intensity monitors, 13 horizontal and 11 vertical. The detectors are standard design split plate Beam Position Monitors. These intercept no beam and will provide position information during normal operation. All units have intensity and position readouts for each NuMI batch.

Toroids

Toroids are used for intensity measurements as they provide better accuracy than BPMs, are stable, reliable and capable of absolute calibration. There are two toroids in the NuMI line. TOR101 is located after the first quadrupole. TORTGT is located in the pre-target area just upstream of the target.

Beam Loss Monitors

Standard sealed loss monitors are placed at every location along the beamline where the aperture becomes smaller as well as at every second magnet in bend strings. Each loss monitor was calibrated at the Radiation Test Facility. Loss monitor calibration will be checked with some regularity by inserting known loss points in the beam; the profile monitors.

The loss monitor electronics is the same as that developed for the Main Injector beamlines, where several decades of linearity have been demonstrated. These monitors provide the first warning of many types of beam delivery problems.

Total Loss Monitors

As the name implies, the Total Loss Monitor (TLM) system provides an integrated beam loss measurement along the line. There are 4 NuMI TLM regions: TLMNS covers extraction and transport to the NuMI Stub, TLMCTU covers the Upper Hobbit region of the Carrier Tunnel, TLMCTD covers the Lower Hobbit region of the Carrier Tunnel, and TLMPT covers the Pre-Target region.

The TLM is a 7/8" heliax cable laid into the cable tray adjacent to the beamline. A gas mixture of Ar-CO_2 flows between the center conductor and the outer shield. The shield is held at 800 V. The current on the center conductor is proportional to the beam loss along the entire length of the cable.

4.4 Vacuum Systems

Transport of the NuMI proton and hadron beams requires that various levels of vacuum be established in the MI tunnel, extraction stub, carrier pipe, pre-target area and decay pipe. Since the NuMI beamlines are single pass, requirements are not as stringent as they are in a circular machine. The second vacuum system is the 675 m long decay pipe, which has a very large evacuated volume.

The primary beam transport system starts in the extraction area at the Lambertson magnets and continues through the carrier pipe, pre-target area and just into the target pile. The vacuum requirements for clean beam transport are 10^{-6} Torr in the vicinity of the beam instrumentation and 10^{-5} Torr elsewhere. Since there is no window to isolate the NuMI vacuum system from the Main Injector, the NuMI vacuum system operates in the 10^{-8} Torr region.

The 6' diameter decay pipe starts just downstream of the target pile and extends 675 meters to just upstream of the beam absorber. This system is operated below one Torr to

minimize interactions with the secondary beam. The decay pipe vacuum skid is located in the Absorber Access Tunnel which is accessible from the MINOS service building.

4.5 Water Systems

There are 7 water systems in the NuMI facility. Each has one or more pumps which are protected by a series of interlocks. These pump interlocks are implemented in a Programmable Logic Controller (PLC). Each system has a number of instruments, which output analog variables to be displayed on an ACNET parameter page and a synoptic display program. Typically, these variables include water system pressures, temperatures, flow rates, expansion tank liquid levels, and resistivity. Each system generates digital status for reading by ACNET. Each system receives one or more digital commands from ACNET. These signals are used to start or stop pumps based on an operator's command at the ACNET console.

4.5.1 MI-62 LCW System

The MI-62 LCW system provides cooling water to all extraction and pre-target magnets. The MI-62 LCW system rejects its heat to the pond G pond water system. There are two installed pumps; one pump runs, and the other is in hot stand-by. Controls for the MI-62 water system also include controls and instrumentation for the pond water (PW) system.

Approximate System Volume:	4200 gallons
Approximate Pump Specifications:	600 gallons per minute 440 feet total developed head 125 horsepower
Heat Load	760 kW
Nominal Heat Exchanger Capacity	1200 kW

4.5.2 MINOS LCW system - PPD

This system provides cooling water to the MINOS Near Detector Coil, its power supply and the electronics racks located in the MINOS Near Detector Hall. Operation of this system is the responsibility of the Particle Physics Division. The MINOS LCW system rejects its heat to a FESS provided chilled water system in the MINOS Service Building and MINOS Cavern.

Approximate System Volume:	310 gallons

Approximate Pump Specifications:	145 gallons per minute
	110 feet total developed head
	3 horsepower
Heat Load	109 kW
Nominal Heat Exchanger Capacity	150 kW

4.5.3 Decay Pipe Cooling RAW system.

This system provides cooling to the decay pipe located in the tunnel between the NuMI Target Hall and the NuMI Absorber Cavern. The Decay Pipe Cooling RAW System rejects its heat to a FESS provided chilled water system at the upstream end of the decay pipe and also rejects its heat at the downstream end to the same FESS provided chilled water system that accepts heat from the MINOS LCW System. There are two installed pumps; one pump runs, one in hot stand-by. The water in this system will become activated.

Approximate System Volume:	725 gallons
Approximate Pump Specifications:	24 gallons per minute
	270 feet total developed head
	7.5 horsepower
Heat Load	140 kW
Nominal Heat Exchanger Capacity	150 kW

4.5.4 Absorber RAW System

This system provides cooling to the NuMI Absorber. The Absorber Cooling RAW system rejects its heat to an Intermediate Water System, which in turn rejects its heat to a pond water system at the MINOS service building. There are two installed pumps; one pump runs, one in hot stand-by. Control of the intermediate system is within the scope of the NuMI Water Systems Controls but the pond water system is not.

Absorber RAW System Volume:	90 gallons
Approximate Pump Specifications:	506 gallons per minute
	65 feet total developed head
	3 horsepower
Heat Load	150 kW
Nominal Heat Exchanger Capacity	150 kW

Absorber Intermediate Cooling System:

| Intermediate Cooling System Volume: | 880 gallons |

Approximate Pump Specifications:	50 gallons per minute 52 feet total developed head 3 horsepower
Heat Load	150 kW
Nominal Heat Exchanger Capacity	150 kW

4.5.5 Target & Baffle RAW System

This system provides cooling to the NuMI Target and Beam Baffles located in the NuMI Target Hall. There are two installed pumps; one pump runs, one in hot stand-by. This system rejects its heat to the MI-62 LCW system.

Approximate System Volume:	85 gallons
Approximate Pump Specifications:	10gallons per minute 42 feet total developed head 1/2 horsepower
Heat Load	~5 kW
Nominal Heat Exchanger Capacity	20 kW

4.5.6 Horn 1 RAW System.

This system provides cooling to Horn 1 located in the NuMI Target Hall. The Horn 1 RAW System rejects its heat to a FESS provided chilled water system. There are two installed pumps, one pump runs, one in hot stand-by. Control of this FESS provided chilled water system is outside of the scope of the NuMI Water Systems Controls.

Approximate System Volume:	105gallons
Approximate Pump Specifications:	110 gallons per minute 106 feet total developed head 5 horsepower
Heat Load	43.5 kW
Nominal Heat Exchanger Capacity	90 kW

4.5.7 Horn 2 RAW System.

This system provides cooling to Horn 2 located in the NuMI Target Hall. There are two installed pumps, one pump runs, one in hot stand-by. The Horn 2 RAW System rejects its heat to a FESS provided chilled water system.

Approximate System Volume:	95 gallons
Approximate Pump Specifications:	110 gallons per minute 103 feet total developed head 5 horsepower
Heat Load	40 kW
Nominal Heat Exchanger Capacity	50 kW

4.6 Beam Absorber

The function of the hadron absorber is to absorb the energy of all remaining hadrons in the beam at the end of the decay pipe. The absorber design has a water-cooled aluminum core surrounded on five sides by steel shielding. On the beam east side, and at the downstream end, there is an additional layer of shielding concrete, three feet in thickness.

US shielding has penetrations for

- DS Hadron Monitor

- Pipe to Vacuum Pump
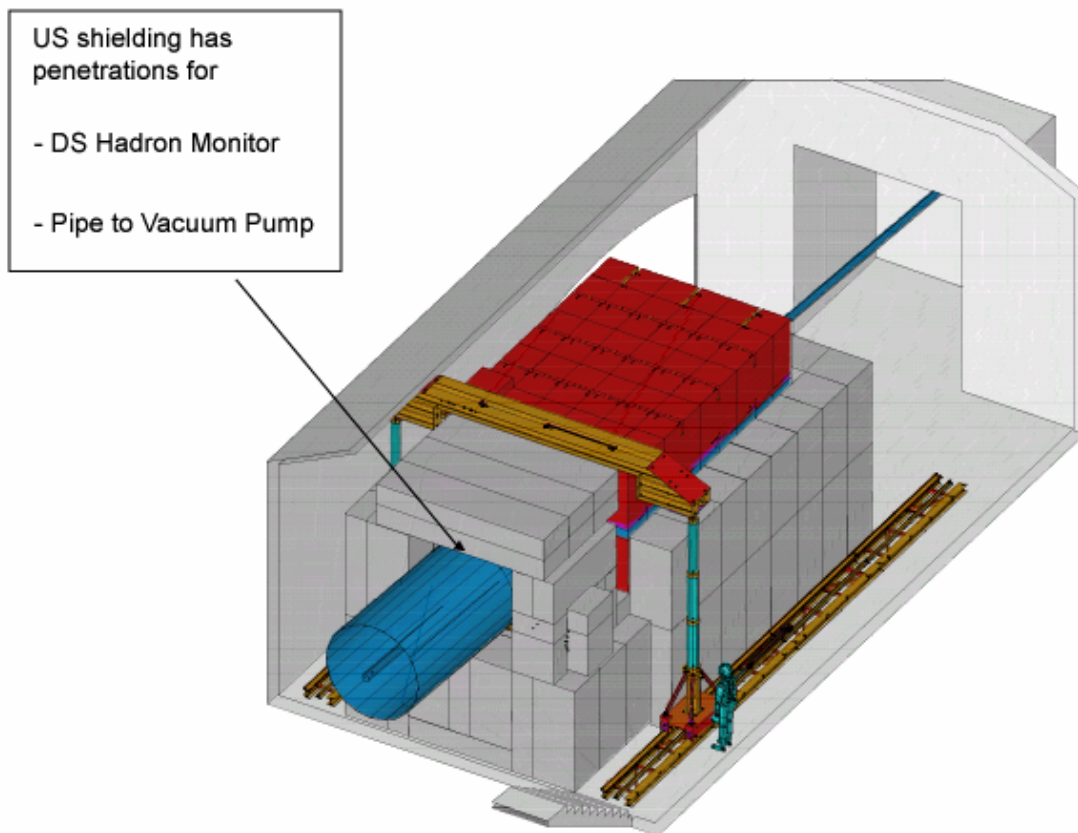
Based on the expected beam energy deposition shown in **Table 4.6–1**, a water-cooled Al core was designed as shown in **Figure 4.6-1**.

Total energy in the beam	121.2 kJ
Energy of primary protons	99.7 kJ
Energy of secondaries: pi; p	16.1 kJ
n; e; gamma	5.4 kJ
Average beam power	64 kW

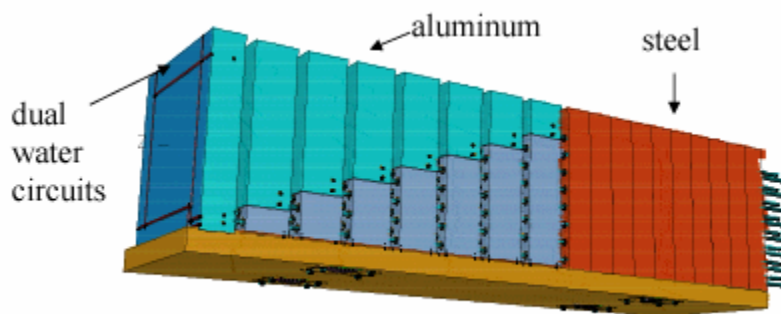**Table 4.6-1** Beam parameters in front of the absorber for the ME beam in normal operation.

Fig. 4.6-1 Absorber Core

 The transverse dimensions of the core are 51" x 51", with eight water-cooled aluminum modules each 12" thick, and 10 layers of steel each 9.1 inches thick. Each aluminum module has two independent water circuits. The steel layers are not water-cooled.

5 Controls

Controls for NuMI are comprised of generally standard interface and networking components. These include a combination of VME, IRM, CAMAC and PLC hardware with necessary and appropriate modules to afford monitor and control of technical equipment through ACNET.

5.1 Controls Locations

Controls for NuMI are installed at eight distinct geographical locations. Three of these locations are already outfitted with basic Controls infrastructure. Major items of equipment or systems to be controlled and monitored are listed for each of the locations in **Table 5.1-1**.

	MI-60 SB South	MI-60 SB North	MI-62 SB	MI-65 SB	Target Hall PS Support Room	MINOS SB	MINOS Near Detector Hall	Absorber Access Tunnel
	60S	**60N**	**62SB**	**65SB**	**THSR**	**MSB**	**MND**	**AAT**
Power Supplies								
Single Turn Extraction Kicker	X							
Lambertsons		X						
Dipole Magnets		X	X	X				
Quadrupole Magnets		X	X	X				
Trim Correction Elements		X		X				
Focusing Horns Including Stripline					X			
Loss and Profile Monitor High Voltage		X	X	X	X			
Near Detector Analysis Magnet							X	
Vacuum								
Primary Beam Transport - Including Isolation Valves, Gauges & Ion Pumps		X	X					
Decay Pipe (PLC)								X
Fluid Systems								
Flourinert Cooling for Extraction Kickers	X							
MI-62 LCW and Pond Water Systems (PLC)			X					
Target & Baffle RAW System (PLC)					X			
Horn 1 RAW System (PLC)					X			
Horn 2 RAW System (PLC)					X			
Target Pile Air Cooling System					X			

	MI-60 SB South	MI-60 SB North	MI-62 SB	MI-65 SB	Target Hall PS Support Room	MINOS SB	MINOS Near Detector Hall	Absorber Access Tunnel
	60S	**60N**	**62SB**	**65SB**	**THSR**	**MSB**	**MND**	**AAT**
(PLC)								
MINOS LCW System (PLC)							X	
MINOS Sump Pumps						X	X	
Decay Pipe Cooling RAW System (PLC)					X			X
Intermediate Water Cooling for Absorber RAW System (PLC)								X
Absorber Cooling RAW System (PLC)								X
Instrumentation								
Primary Transport Beam Position Monitors		X		X				
Beam Profile Monitors		X		X				
Loss Monitors		X	X		X			
Total Loss Monitors			X					
Beam Intensity Toroids			X		X			
Baffle and Target Instrumentation (PLC)					X			
Target Budal Monitors					X			
Positioning Systems for Target and Horn 1					X			
Horn 1 and 2 Module and Stripline Instrumentation (PLC)					X			
Horn Bdot Magnetic Field Probes					X			
Absorber Instrumentation (PLC)								X
Hadron Monitor at DS End of Decay Pipe								X
Muon Monitors at Muon Alcoves #1, #2 and #3								X
Beam Permit System - Process Channel Interface (7 Total)	X	XX	X	X	XX			
ACNET Connectivity								
Ethernet	X	X	X	X	X	X	X	X
VME	X	X	X	X	X			X
Internet Rack Monitor - IRM					X			
Programmable Logic Controller - PLC		X	X	X	X		X	X
CAMAC	X	X	X	X	X	X	X	X

Table 5.1-1 Technical Equipment Interfaced to the Control System versus Location

5.2 Accelerator Clocks and NuMI Operation

The present accelerator complex uses a number of clock systems to control devices and to time beam transfers. Of particular interest to NuMI operations are the following:

TCLK The primary accelerator time clock is a 10 MHz clock known as TCLK. A TCLK event is realized by the transmission of 8 bits of data enveloped by a start and parity bit in the serial clock stream. TCLK events are designated by a two-character hexadecimal number preceded by a dollar sign and range from $00 through $FF.   Six new or redefined TCLK events have been assigned to accommodate NuMI operations. These are $23, $A5, $19, $A9, $A6 and $A8. NuMI operations are planned to occur in a new Main Injector reset cycle signed by **TCLK $23**. This reset cycle is unique in that it can simultaneously support P-Bar production and NuMI operations.   In the dual mode, one to five batches of Booster beam may be loaded into MI for NuMI. The total cycle time for the Main Injector running under the $23 reset is optimally established at 1.8 seconds.

MIBS The Main Injector has a separate beam synchronous clock system, MIBS, that is locked in frequency to the Main Injector rf system. This clock operates at approximately 7.5 MHz (rf/7) and is used to coordinate Main Injector transfers and beam related diagnostics. A most significant event on the MIBS clock is $AA, the revolution marker. For the MI, the $AA event occurs approximately every 10 microseconds.   MIBS event $74 has been assigned to initiate the extraction of 120 GeV beam for NuMI. When issued, this extraction event is always synchronous with respect to the MIBS $AA revolution marker event.

Timing observations for the Main Injector $29 cycle for antiproton production are listed in **Table 5.2-2**. Expected timing for the Main Injector $23 cycle for antiproton production and NuMI Operations are listed in **Table 5.2-3**. TCLK and MIBS events of interest to NuMI operations are listed in **Table 5.2-4**.

Timing Observations of MI $29 Cycle for P-Bar Production Cycle

Event	Description / Comment	Time in Milliseconds	Note
$80	3 x 15 Hz Ticks Before $29 MI Reset or -201 ms	-201.0	
$29	Main Injector Reset	0.0	1
$22	Start of Ramp	89.0	
$25	Start of Flattop	778.9	
MIBS $79	Initiate antiproton production Beam Transfer	838.9	
	MI-52 Kicker Fire Time MIBS $79 + 24.918 MR Rev	839.2	
$26	End of Beam Operations	848.9	
	Total $29 Cycle Time	1,466.7	2
	Flattop to Actual antiproton production Beam Extraction	60.3	

Note 1   The $29 to $22 Interval Accommodates One $14 Booster Batch to Main Injector.

Note 2   The Current $29 Cycle is Judged to be Twenty-Two 15 Hz Ticks Long or 1.467 Seconds

Table 5.2-2   Timing Observations for MI $29 Cycle for antiproton production

Expected Timing for MI $23 Cycle for P-Bar Production and NuMI Operations

Event	Description / Comment	Time in Milliseconds	Note
$80	Signature Event for antiproton production Cycle	?	**3**
$A5	Signature Event for NuMI Beam Cycle	-0.001	**4**
$23	Main Injector Reset	0.0	**5 & 6**
$22	Start of Ramp	422.3	
$25	Start of Flattop	1,112.2	
MIBS $79	Initiate P-Bar Production Beam Transfer	1,172.2	
	MI-52 Kicker Fire Time MIBS $79 + 24.918 MI Rev	1,172.5	
MIBS $74	Initiate NuMI Beam Extraction	1,173.3	**7**
	I:KPS6N Kicker Fire Time MIBS $74 + 20.xxx MI Rev	1,173.5	**8**
$26	End of Beam Operations	1,182.2	
	Total $23 Cycle Time	1,800.0	**9**
	Flattop to Actual antiproton production Beam Extraction	60.3	
	Flattop to Actual NuMI Beam Extraction	61.3	

Note 3 $80 May be Placed Before or After the $23, but Must be Before the $14.

Note 4   The $A5 Event is Now Expected to be Immediately Before the $23 MI Reset. That Stated, $A5 May be Placed Before or After the $23, but Must be Before the $19s.

Note 5   The $23 to $22 Interval Will Accommodate Six Booster Batches to Main Injector. Normally a Single $14 Batch for P-Bar Production and 5 x $19 Batches for NuMI.

Note 6   The $29 to $22 Interval of 89 ms is Extended by Five 15 Hz Ticks for the $23 Ramp Scenario. Subsequent Times Generally Advance by 333.3 ms.

Note 7   Exact Placement of MIBS Extraction Event is Subject to Observed Peak of Longitudinal Bunch Length and Number of Integral MI Turns of Beam After MIBS $74.

Note 8   Time is About 1 ms After antiproton production Beam Extraction When Longitudinal Bunch Length is Peaked. 20 MI Revolutions is the Suggested Integral Value of Delay After MIBS $74. ".xxx" Fractional Turn Delay to be Field Determined.

Note 9   The Expected $23 Cycle is Judged to be Twenty-Seven 15 Hz Ticks Long or 1.8 Seconds

Table 5.2-3   Expected Timing for MI $23 Cycle for antiproton production and NuMI Operations

NuMI TCLK and MIBS EVENTS

TCLK	DEFINITION	COMMENT
$A5	NuMI Reset for Extracted Beam	Expected to be Closely Synchronous With and Well in Advance of NuMI Extracted Beam. Primary Reset for NuMI Ramped Devices.
$23	Main Injector Cycle Reset for Antiproton Production and NuMI Operations	Usually Has Beam for Both Antiproton Production and NuMI Operations. But Could Have Beam for Only One Destination.
$14	Booster Reset for Antiproton Production Beam	Normally One High Intensity Batch.
$19	Booster Reset for NuMI Operations Beam	Normally One to Five Batches for NuMI with Programmable Intensity.
$52	Beam for Previous Booster Reset Will Be Accelerated.	A Generic Event.
$53	Beam for Previous Booster Reset Will Not Be Accelerated.	A Generic Event.
$1F	Booster Beam About to be Transferred to Main Injector	A Generic Event.
$22	Main Injector Ramp Begins	A Generic Event.
$25	Main Injector Flattop	A Generic Event.
$81	Reflected MIBS Event $79	Expected to be Synchronous Within a Few Microseconds.
$A9	Reflected MIBS Event $74	Expected to be Synchronous Within a Few Microseconds.
$27	Detected Fall of the Main Injector Beam Permit	Fires the Main Injector Abort Kicker
$2F	Fire the Main Injector Abort	Happens Every Cycle.
$26	End of Beam Operations in the Main Injector	All Beam Should be Gone.
$A6	NuMI Beam Permit Has Fallen to Non-Permit State	Serves to Inhibit Accelerating Beam Associated With Booster $19 Reset. Also Will Inhibit Generation of MIBS $74.
$A8	NuMI Beam Permit System Reset	Issued by Operator Command. Rcvd by C200 and C201 Modules. Clears Latched Inputs of C200.
$FA	Reflected MIBS $ED	A Generic Event.

MIBS	DEFINITION	COMMENT
$AA	Main Injector Revolution Marker	Once Every 588 RF Cycles. Approximate 10 Microsecond Period.
$79	Initiate Transfer of 120 GeV Antiproton Prod Beam to Antiproton Tgt	Reflected as TCLK $81.
$74	Initiate Transfer of 120 GeV NuMI Beam to NuMI Primary Beamline	Reflected as TCLK $A9.
$ED	Request for a MIBS Transfer Event Has Been Denied	Reflected as TCLK $FA. This is a Generic Event. If One Expects to See $74 or $79 and Does Not, This $ED Event Should Be Generated.

Table 5.2-4 NuMI TCLK and MIBS events

5.3 Beam Permit System

The fundamental design of the NuMI Beam Permit System (NBPS) takes advantage of already designed hardware and methodologies for Beam Permit/Abort that was instituted in the early days of the Tevatron. While not necessarily redundant in architecture, the NBPS is simple and fail-safe in design.

The NBPS is realized by a dedicated fiber optic line linking all of the distinct geographic locations of NuMI controls. Its operation closely resembles that of a simple flip-flop being in either a beam permit or inhibit state. Inputs for the beam inhibit conditions are many, with each being latched. Bringing the NBPS communication line to the beam permit state is singularly accomplished by operator initiation of a specific TCLK event, but only after beam inhibit conditions have been cleared. The state of the line is examined at two significant locations. The NBPS state is examined at MI-60 as a necessary condition to launch the MIBS $74 extraction event and to allow the firing of the NuMI single turn extraction kicker. The NBPS state is also examined at the Main Control Room as an input to the Beam Switch Sum Box (BSSB) as one of the necessary conditions to allow acceleration of beam in the Linac that is destined for NuMI.

The NBPS distinguishes itself from other installed permit systems in the number and type of inputs. Specifically it is intended to monitor as many technical components and sub-systems as practical that portend successful operation of the NuMI beamline and meaningful operations. The NBPS is especially unique in that it examines data for proper state and operation both closely before and immediately subsequent to NuMI beam extraction. Central to this unique capability is the development of the Process Channel Interface (PCI) and its companion ACNET interface, the CAMAC C204 module. The C204/PCI facility is capable of examining analog and digital inputs with respect to down loaded limit values. The decision process is localized, prompt and not centrally reliant on ACNET services for execution. ACNET services are required for set-up.

The following is a condensed list of significant inputs to the NuMI Beam Permit System:

- NuMI Radiation Safety System
- Main Injector Performance Parameters
  o Final orbit positions, MI & P1 line loss monitors, Pbar beam not extracted
- Single Turn Extraction Kicker
  o PS current/volts, Fluorinert cooling status
- Dipole and Quadrupole Magnet Power Supplies
  o PS current, reference & error
- Beam Loss Monitors & Total Loss Monitors
  o Loss reading, HV supply, HV return, gas flow
- Low Conductivity and Radioactive Water Systems
  o Temperature, pressure, pump status, high/low tank level via PLC

- Extraction Beamline Vacuum System
  - Valve status, vacuum level
- Target Hall
  - PLC heartbeat, target chase air-cooling system, Target hall air damper position, baffle temperature,

6 Radiation Safety

The design of the Fermilab Main Injector (MI) permits the acceleration of numbers of protons not previously encountered in the energy regime above 100 GeV. The NuMI Facility design assumes that Main Injector protons will be transported to the target at a maximum intensity of 4×10^{13} protons every 1.87 seconds. This is called the Safety Envelope. Normal running will be allowed up to 10% less than this safety envelope. Physics goals of the MINOS experiment assume a value for beam on target of 3.7×10^{20} protons per year. For the purposes of designing radiation protection for the NuMI Facility, the above intensities translate to a maximum instantaneous proton rate of 2.1×10^{13} protons per second and an annual "dc" average (assuming 55% efficiency for beam) of $\sim 1 \times 10^{13}$ protons per second.

The NuMI primary proton beam and the secondary hadron beam are directed toward the MINOS far detector in Soudan at a 58 mrad downward slope. As a consequence the Target Hall and much of the hadron decay region pass through the local aquifer. This has led to careful consideration and analysis of the processes that might lead to potential contamination of the groundwater resources. The key issue for NuMI is that radionuclides produced in the rock and water surrounding the beam line are produced in the groundwater. Thus we cannot take credit for decay in transit to the groundwater resource as other facilities not constructed so deeply have. Several analyses and designs laid the groundwork for a model suitable for underground beamlines. A Fermilab TM describing this methodology has been completed and approved. It takes into consideration the flow rate of water within the aquifer. Previous methodologies assumed static water conditions which is extremely unrealistic within the aquifer. In the unlined sections of the NuMI tunnel, all the water nearby is captured by the tunnel and thus cannot make it to a well for consumption. In short, the below-ground areas of NuMI function as a large well supplying 250 gallons per minute continuously into the Fermilab ICW system.

Delayed ventilation is used at NuMI to control radioactive air emissions. It is the simplest method and the one historically used at Fermilab. Since the vast majority of the radioactive atoms produced are short lived (20.5 minutes for ^{11}C), a delay time of one hour from production to exhaust will reduce the radioactivity by roughly one order of magnitude at the stack. Since the sealed chase inside the Target Hall is the main source of air activation, the largest delay is from the Target Hall to the vent part way down the Decay Tunnel. The area between the Hadron Absorber and the decay pipe also has high air activation levels. This air is contained within the absorber by carefully sealing cracks.